# Laser Compton Sources Based On Energy Recovery Linacs

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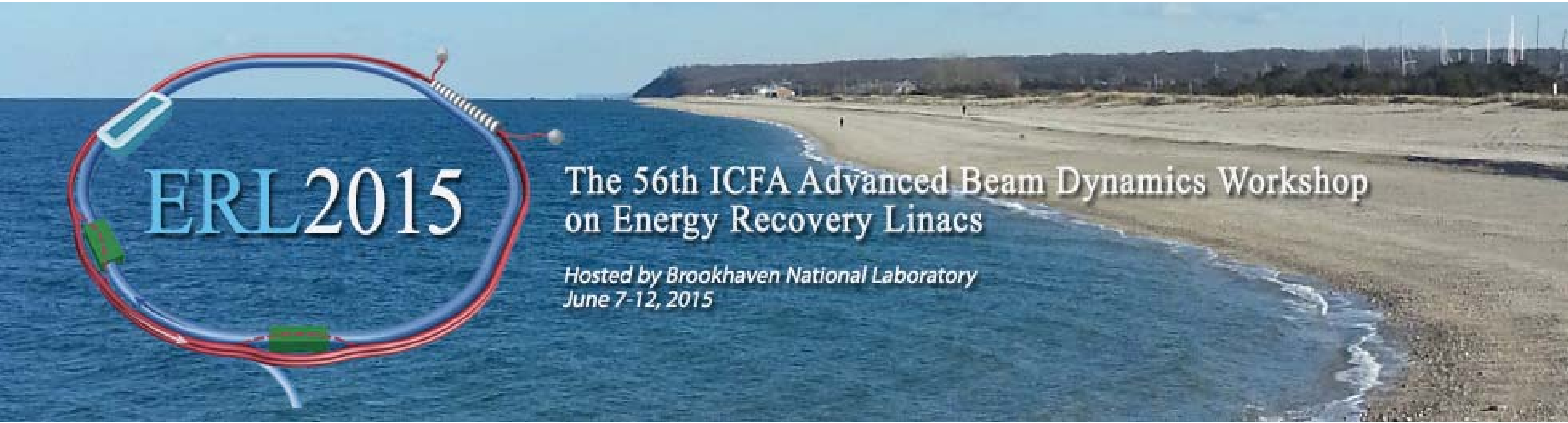
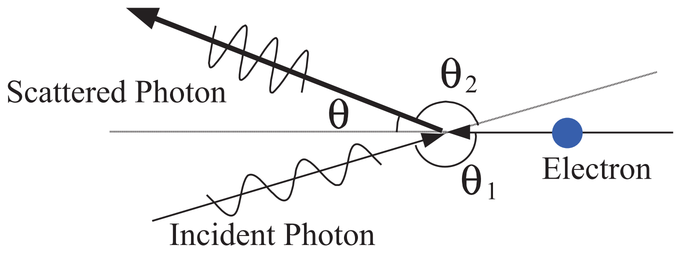
ERL-2015 WS



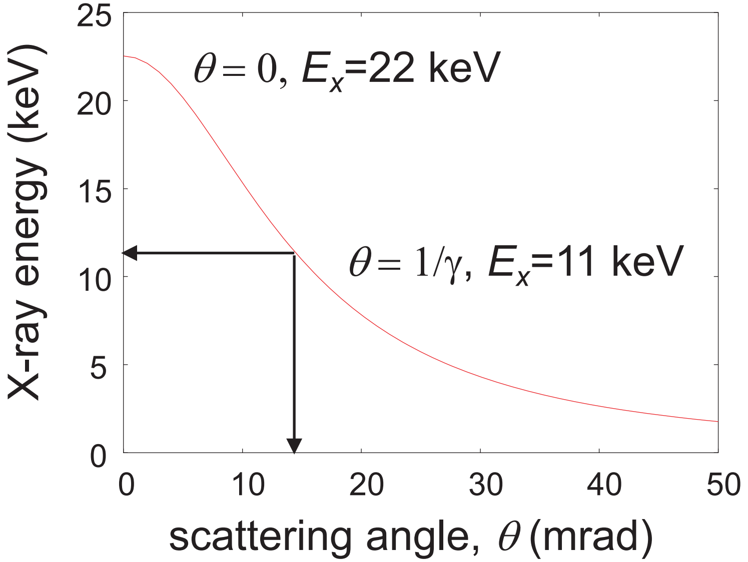
# Laser Compton Scattering (LCS)

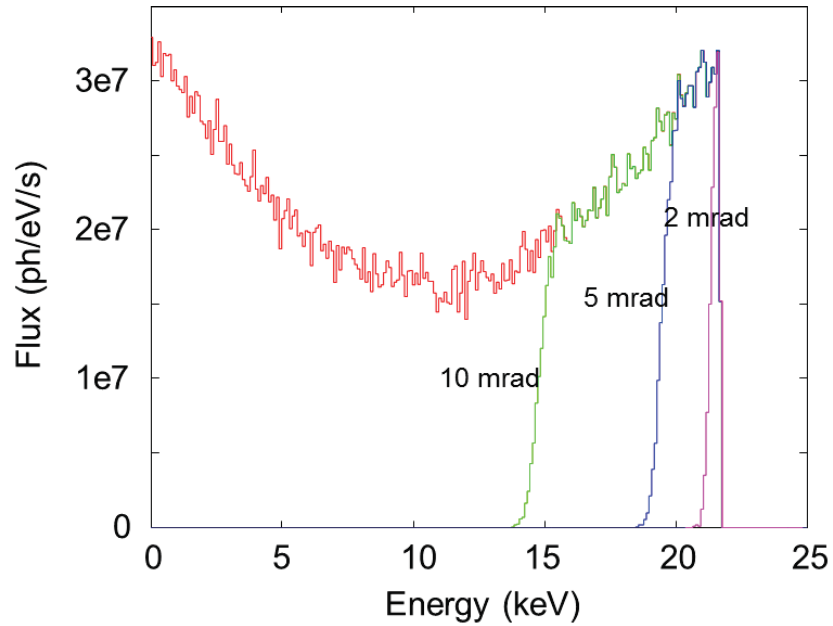



for head-on collision

$$E_X \simeq \frac{4\gamma^2 E_L}{1 + (\gamma\theta)^2 + 4\gamma E_L/(mc^2)}$$

*for example:* $E_e = 35$ MeV, $E_L = 1.2$ eV

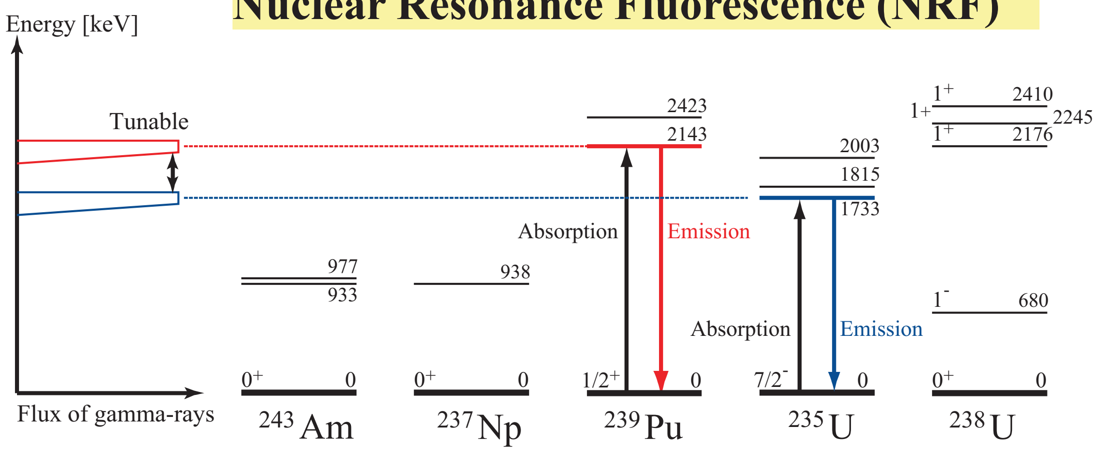


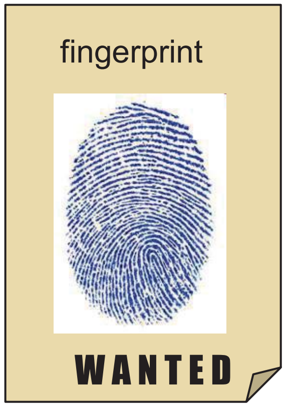




- ✓ Pencil like beam
- ✓ Energy Tunable & quasi-monochromatic
- ✓ Polarized (linear and circular)

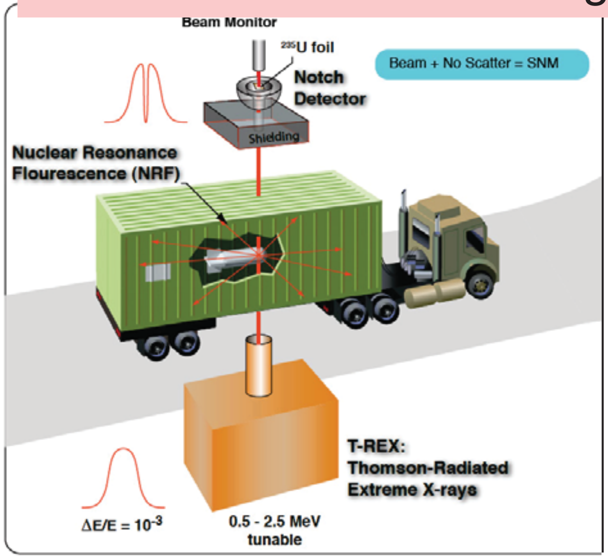
# Nondestructive Detection & Measurement of Nuclear Material

## Nuclear Resonance Fluorescence (NRF)



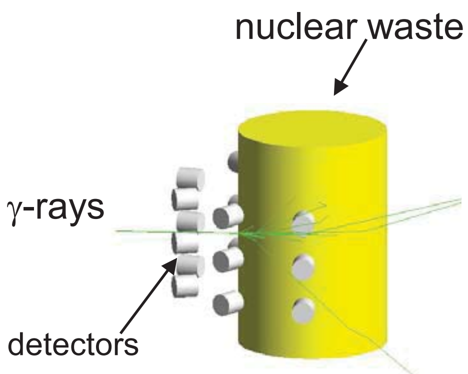




## Detection of SNM in a cargo




SNM: special nuclear material

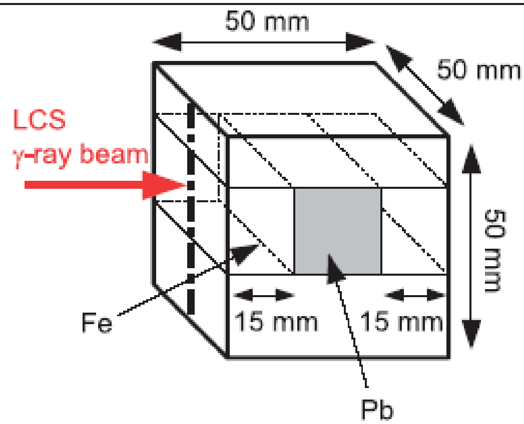
## Management of nuclear material



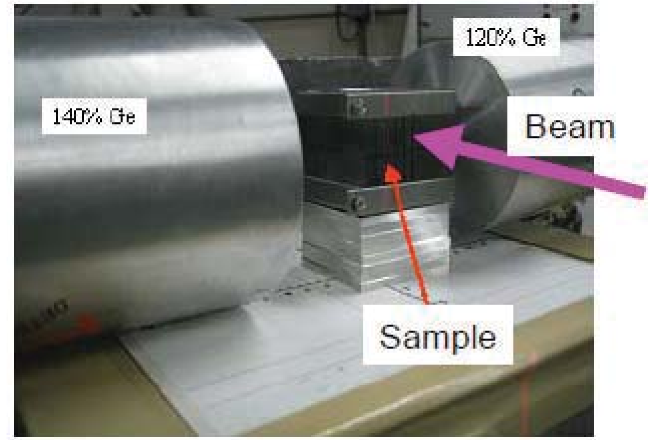

detection and assay of isotopes
- -- U, Pu, and Minor Actinides
- -- alpha emitter
- -- difficult to measure by passive assay

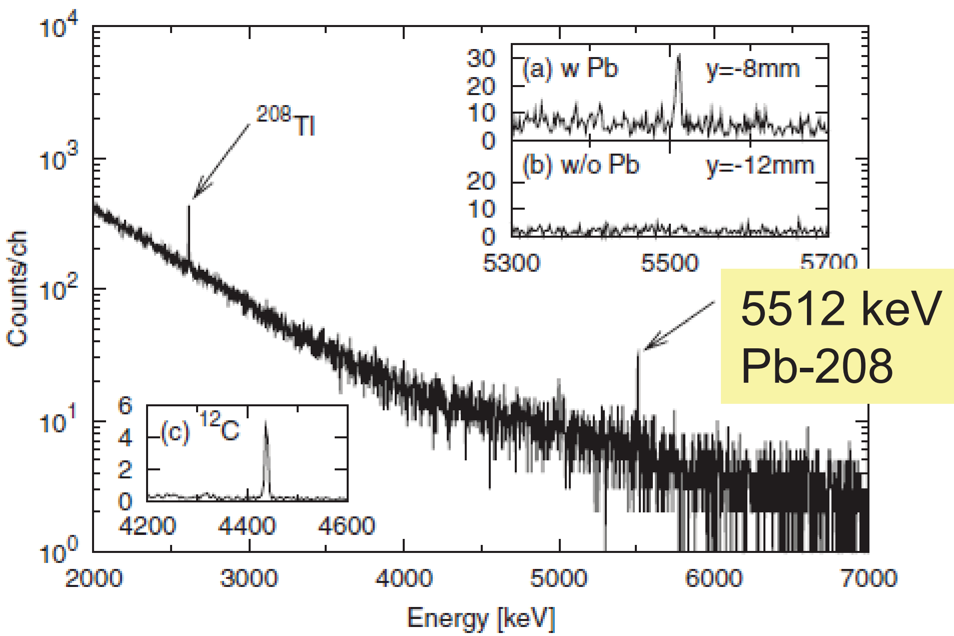
R. Hajima et al., J. Nucl. Sci. Tech. 45, 441 (2008)
J. Pruet et al., J. App. Phys. 99, 123102 (2006)

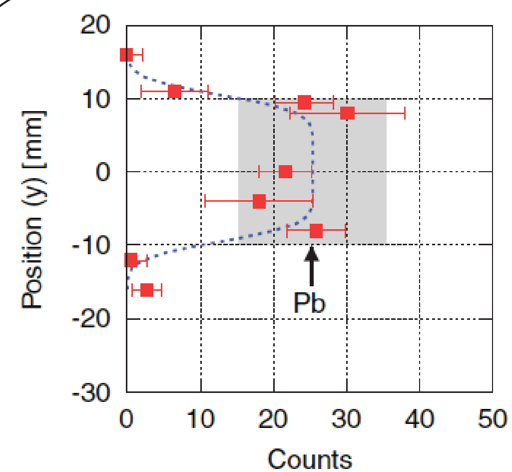
# Experimental Demonstration – nondestructive detection of isotope




Pb block shielded by 15mm-thick iron box




Position and shape of the Pb block were clearly identified.

N. Kikuzawa et al., Applied Physics Express 2, 036502 (2009).

~ 10 hours @ AIST

# Flux and Brightness of LCS sources

Flux : photons/s

$$F_{total} = \frac{16}{3} N_e N_L f \frac{r_0^2}{w_0^2}$$

electron classical radius

electrons

laser photons

collision frequency

collision spot size

Spectral Brightness: photons/s/mm$^2$/mrad$^2$/0.1%BW

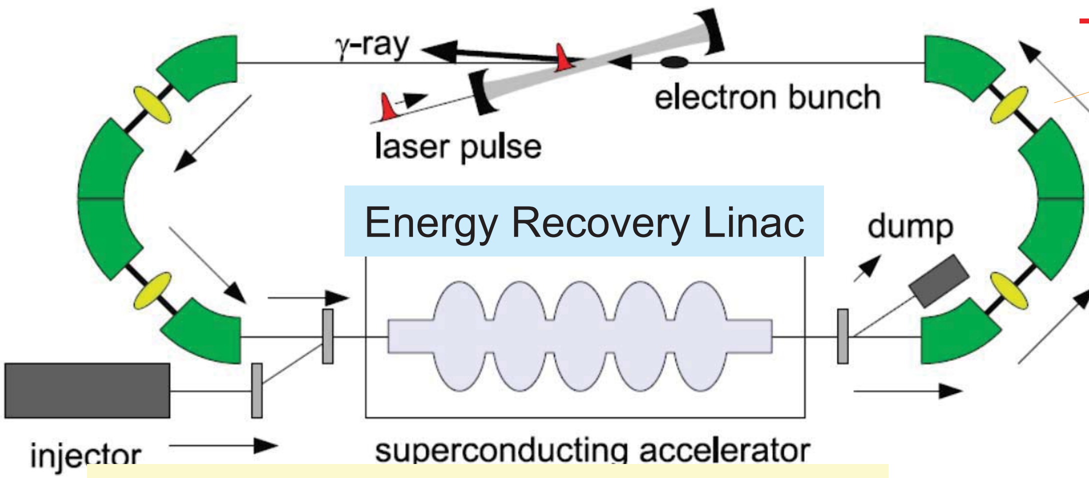
$$B \approx F_{total} \frac{\gamma^2}{\varepsilon_n^2} \times 0.1\%$$

for the higher brightness

- higher collision density
- higher repetition rate
- smaller emittance

# Proposal of ERL-based LCS source

collision at a small spot
collision at a high repetition
→ Low emittance & high-average current



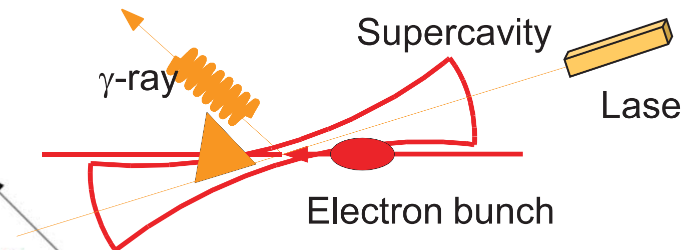

- Electron beam = 350 MeV, 13 mA
- Laser intracavity = 700 kW
- **LCS ~2MeV, $1\times10^{13}$ ph/s**

0.1 ph/eV/s → $10^7$ ph/eV/s

AIST (1st-generation LCS)

ERL

laser enhancement cavity



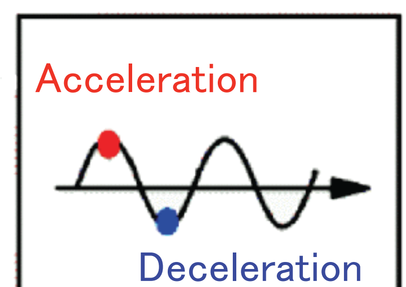

laser photons are recycled

↓

high-flux γ-ray

↑

electron energy is recycled

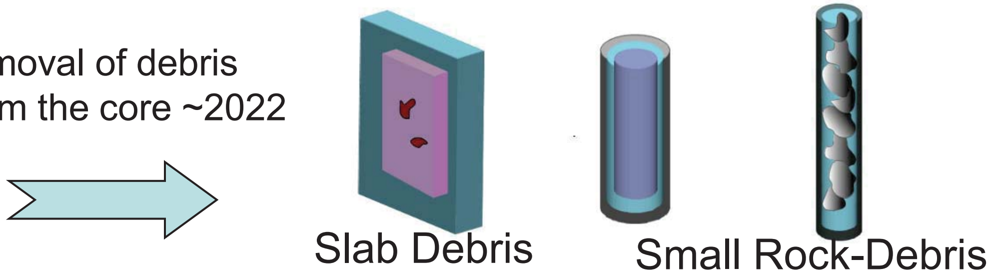


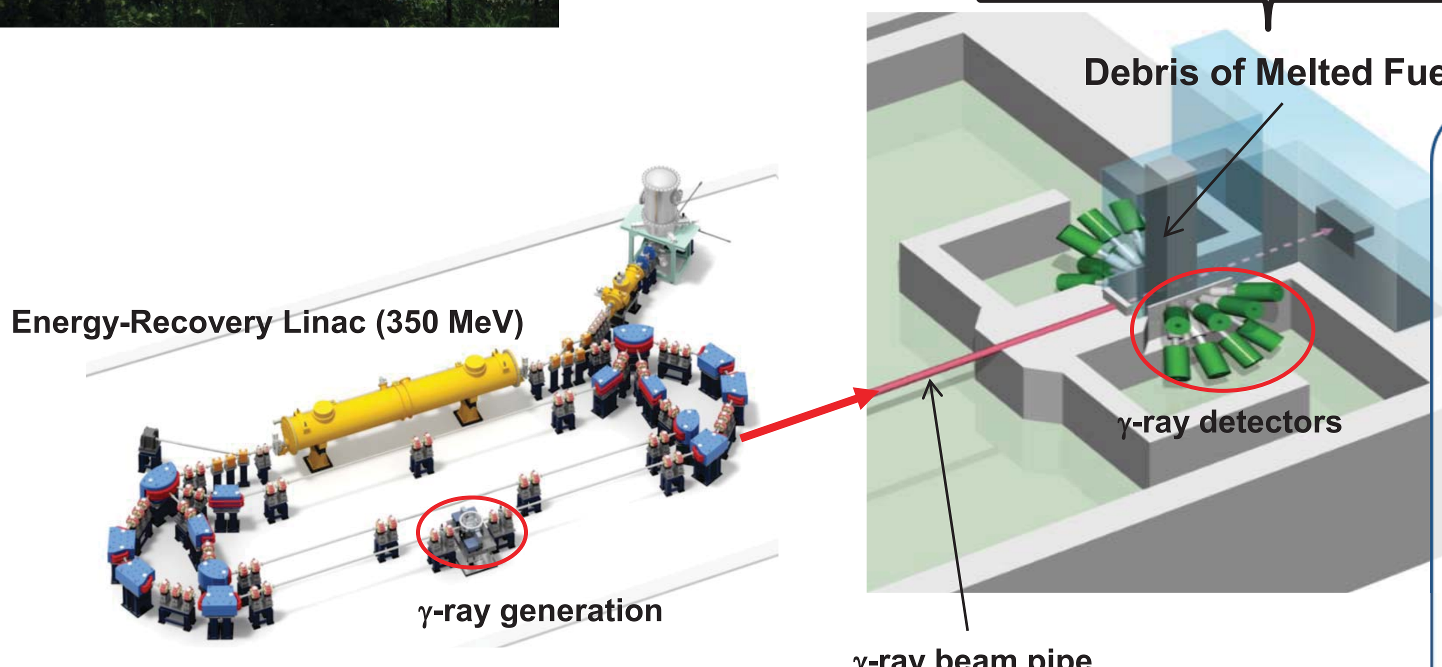

R. Hajima et al., NIM-A608 (2009)

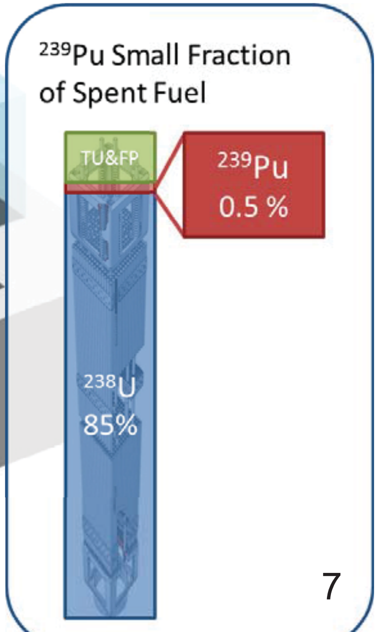
# LCS γ-ray for Fukushima

Measurement of Pu in the melted fuel → necessary for nuclear nonproliferation!

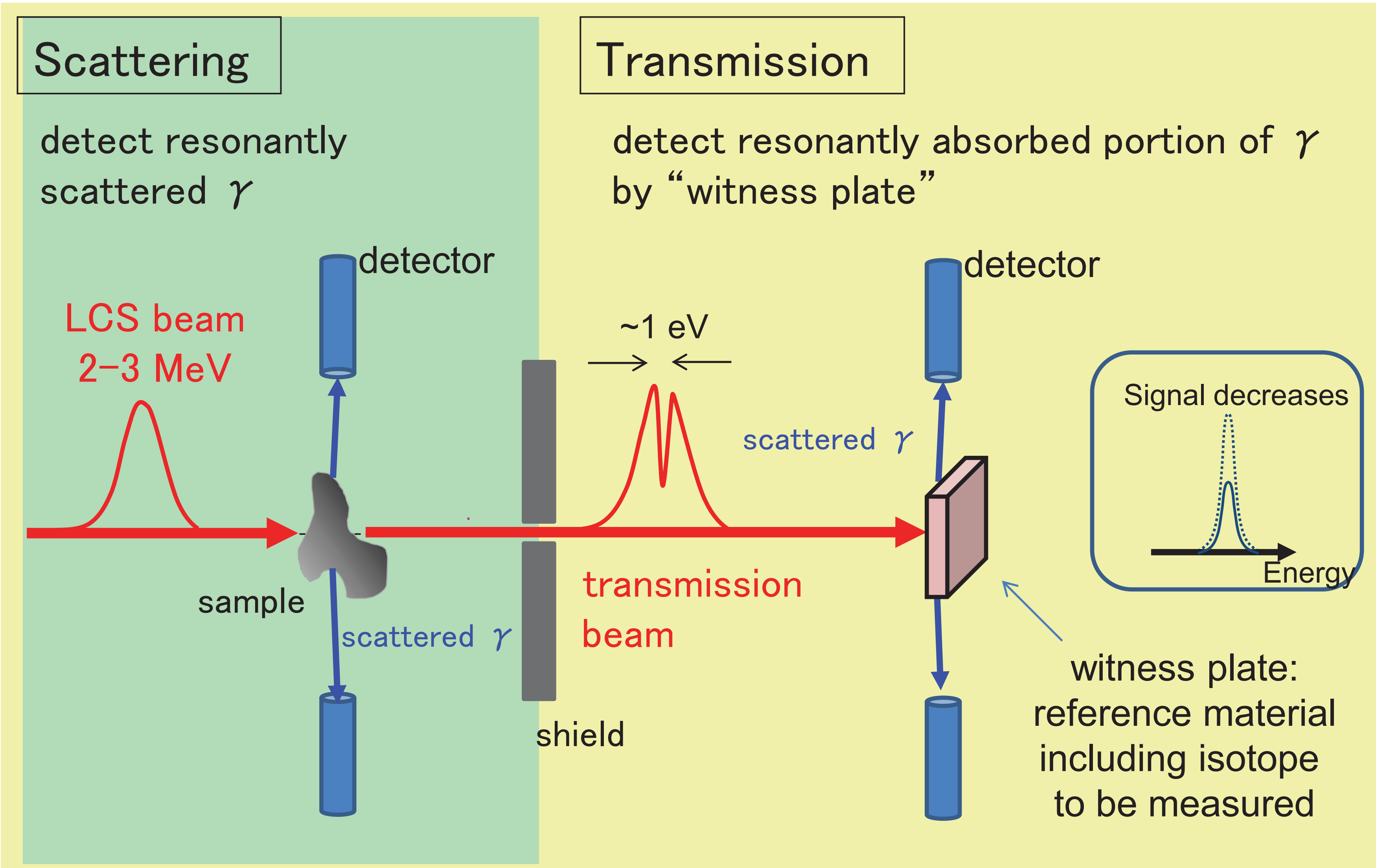
removal of debris from the core ~2022



# Two Measurement Methods

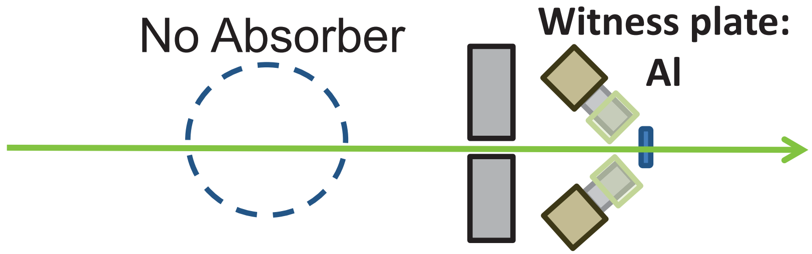


# Demonstration for Debris in a TMI-2 container

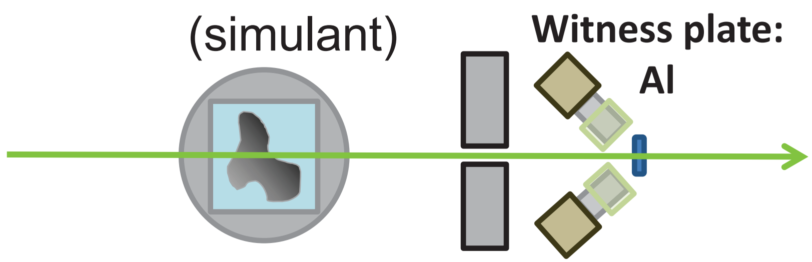
Experiment at Duke/HI$\gamma$S
(LCS $\gamma$ facility)

(TMI: Three Mile Island)

No Absorber

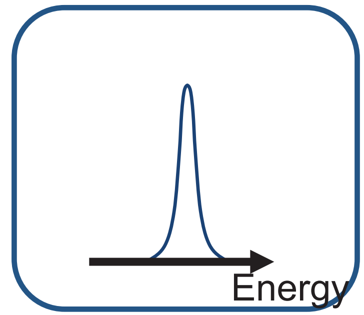



Loaded TMI-2 Container
(simulant)



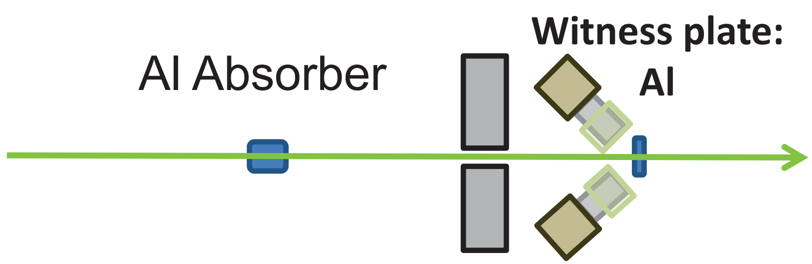

Al witness target chosen as it has strong resonance at similar energies to $^{239}$Pu

No change expected!

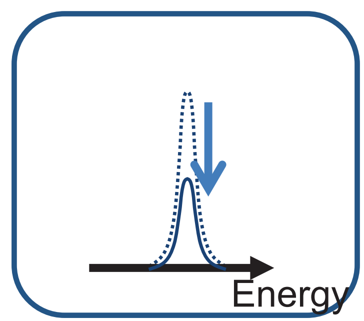



Since witness target is Al, no absorption expected from simulant container

Al Absorber




Signal decrease expected



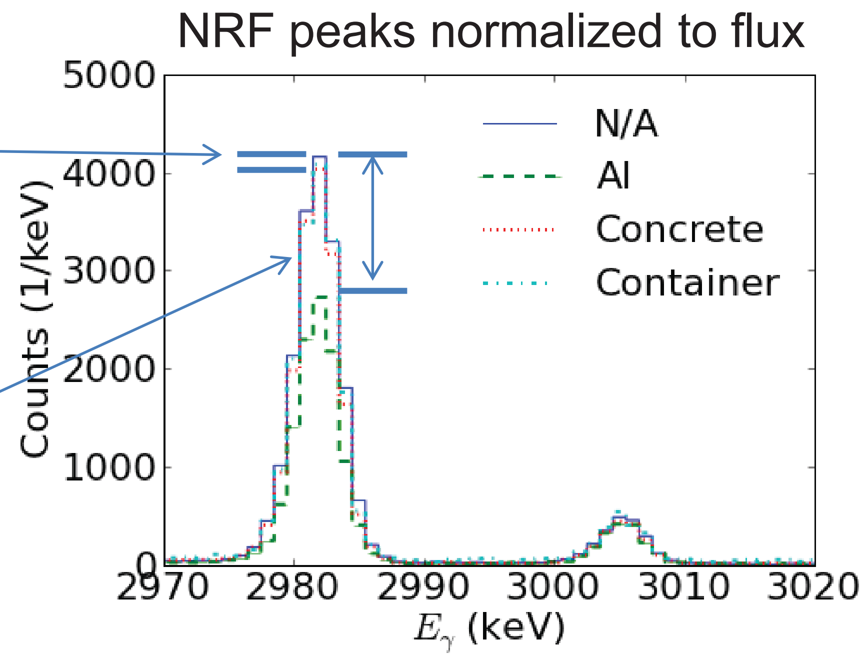

Using Al absorber can verify that experiment was done correctly.

# Demonstration for Debris in a TMI-2 container

**Verified NRF transmission feasible for TMI-2 container!**

Small difference with concrete and container verified – concrete has small amount of Al

Large difference with Al absorber verified



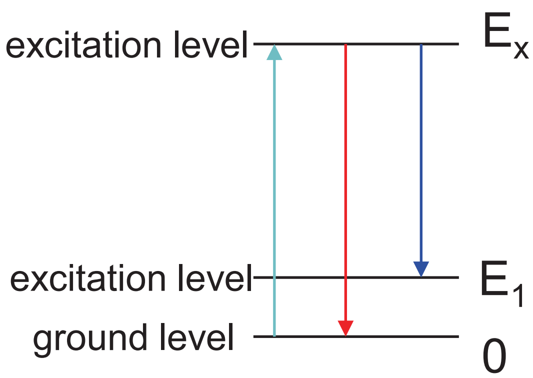

| Absorber | Expected | Measured |
|---|---|---|
| Concrete | 0.96±0.01 | 0.95±0.02 |
| Container | 0.96±0.01 | 0.97±0.03 |
| Al | 0.66±0.01 | 0.65±0.02 |

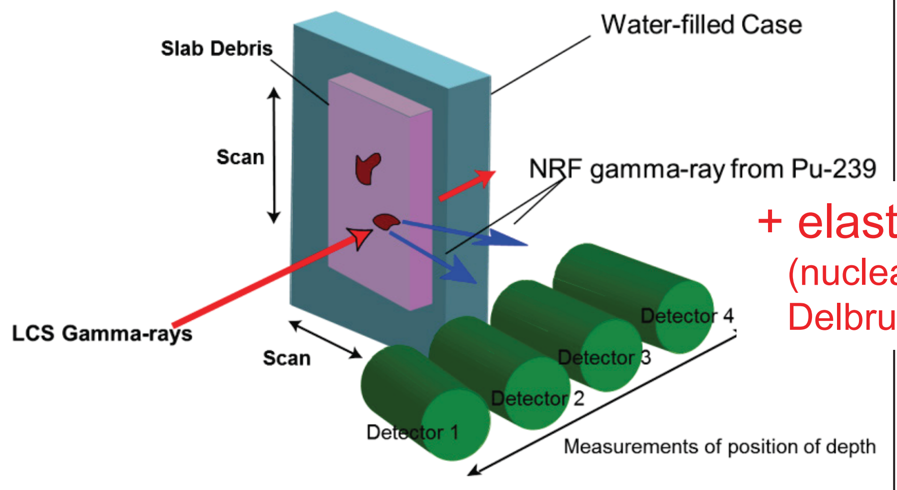
C.T. Angell et al., Nucl. Instr. Meth. B 347, 11 (2015)

Analytical study shows 3.7h – 22h measurement for $^{239}Pu$ in melted fuel with 3% accuracy by using a future ERL-LCS

C.T. Angell et al., to be published

# Detection of decay branch in NRF




+ elastic scattering
(nuclear Thomson, Delbruck scattering)

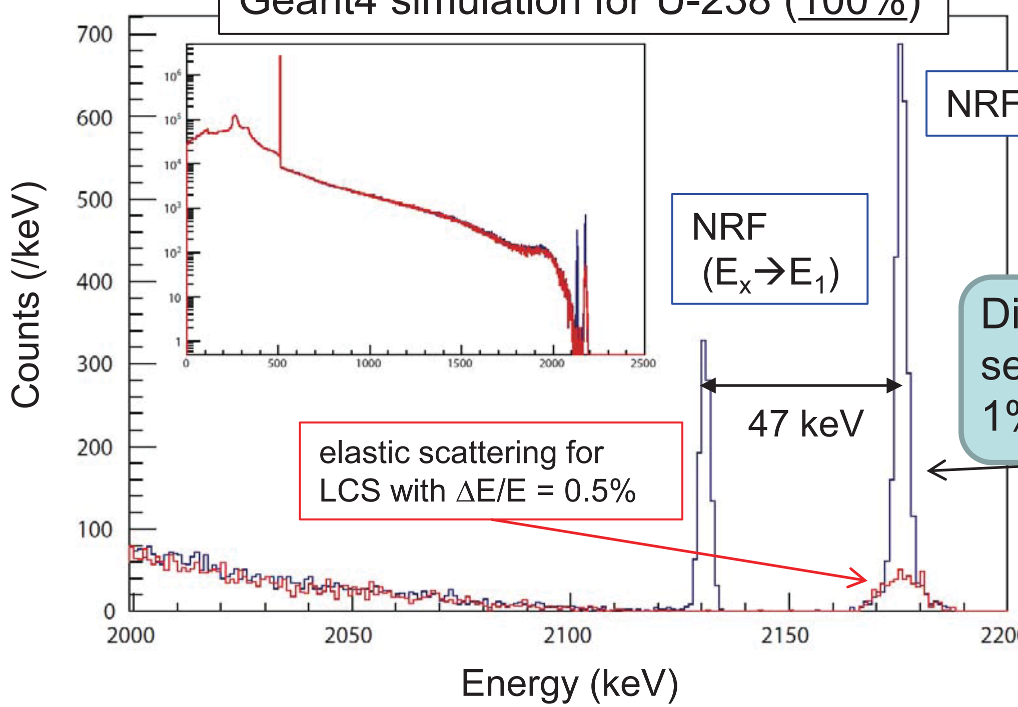
gamma-ray bandwidth

existing LCS : ΔE/E ~ 3-5%

future ERL : ΔE/E < 0.5%

decay branch can separate NRF from elastic scattering

Geant4 simulation for U-238 (100%)

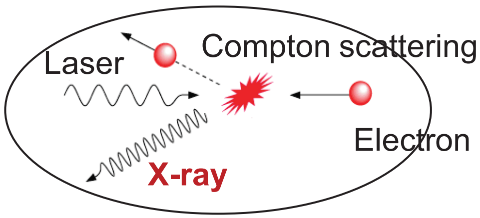


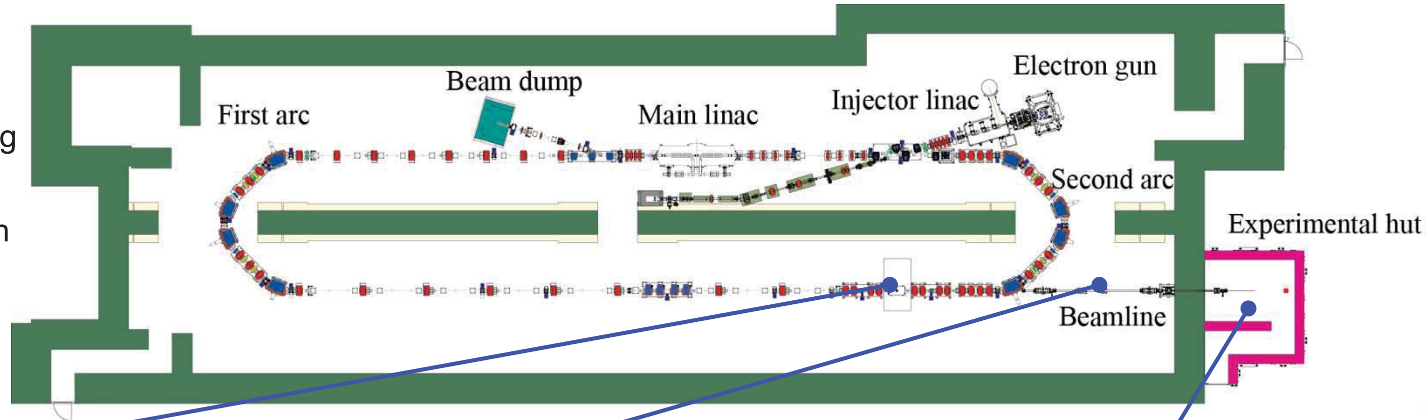

Difficult to see NRF for 1% target

T. Shizuma et al., Nucl. Instr. Meth. A 737, 170 (2014)

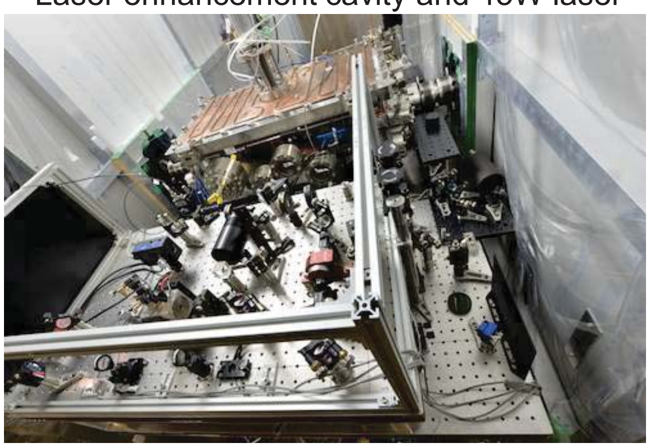
# LCS Experiment at Compact ERL

Demonstration of technologies relevant to future ERL-based LCS sources




Laser enhancement cavity and 45W laser

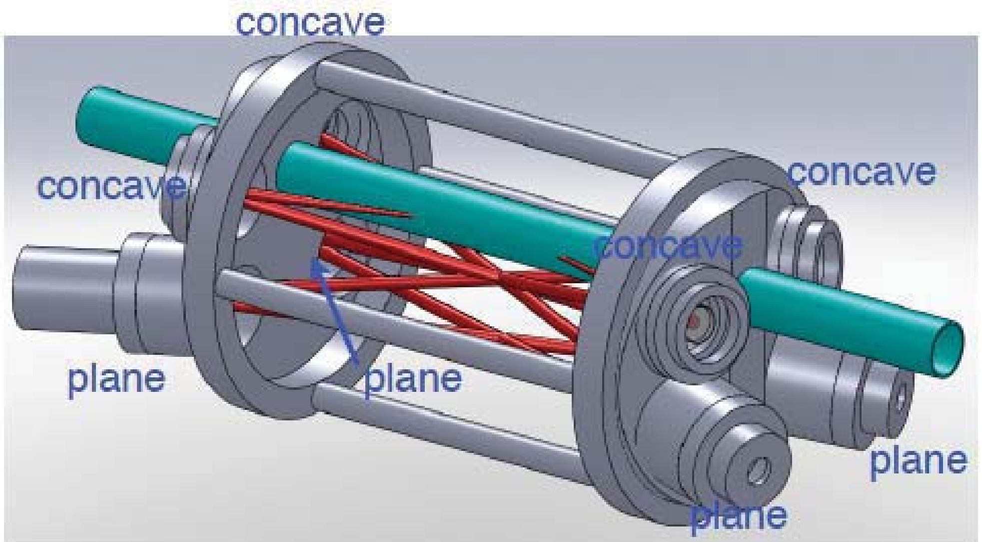


Beam line

Experimental hut

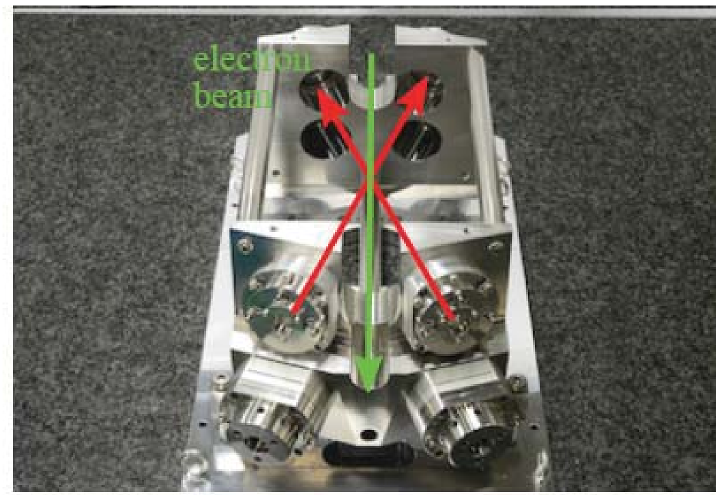

Work supported by:
A government (MEXT) subsidy for strengthening nuclear security (R. Hajima, JAEA), and
Photon and Quantum Basic Research Coordinated Development Program from the MEXT (N. Terunuma, KEK)

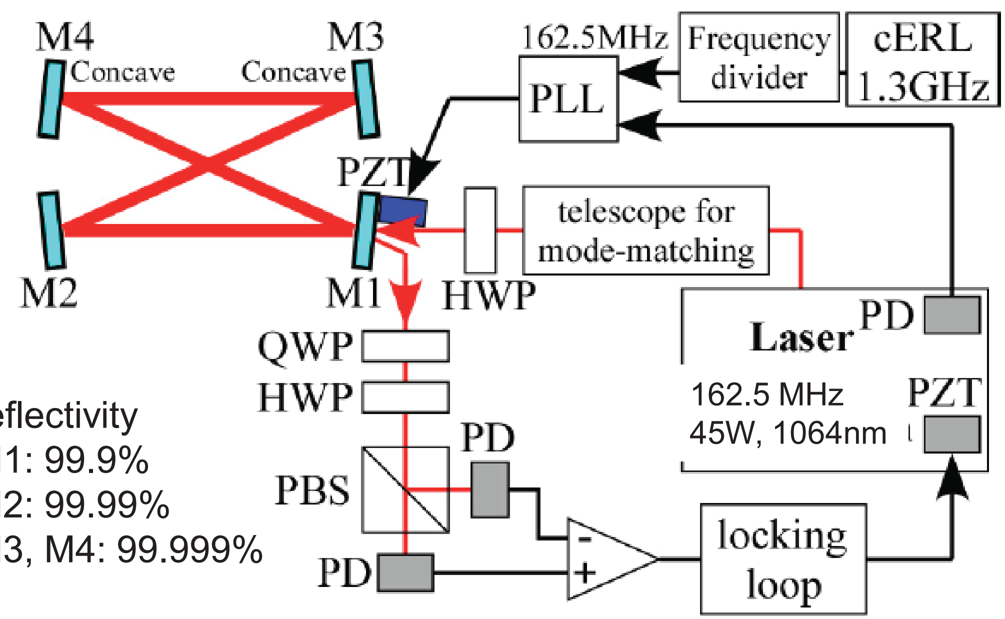
# Laser Enhancement Cavity




Developed by T. Akagi (KEK)

T. Akagi et al., Proc. IPAC-2014, p.2072
A. Kosuge et al., Proc. IPAC-2015, TUPWA-66




reflectivity
M1: 99.9%
M2: 99.99%
M3, M4: 99.999%

waist size: $\sigma$=30$\mu$m

Can store two beams independently

⇩

Fast polarization switch at 325 MHz
or
Double the laser power at LCS

(Single laser for the first experiment)

# Beam Optics for the LCS

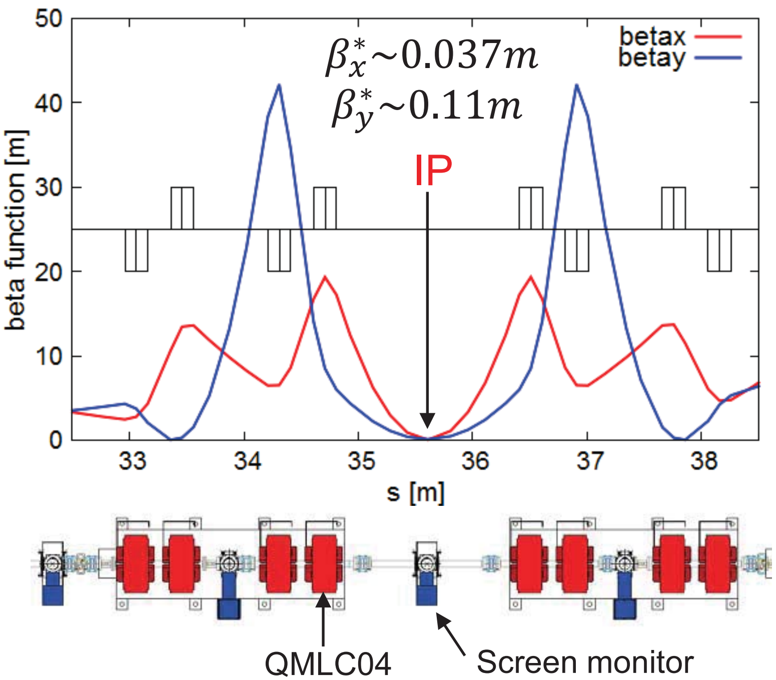
- Low-beta insertion for small beam sizes at IP
- Transport beams to the dump with small beam losses

Beam optics was established

IP: interaction point

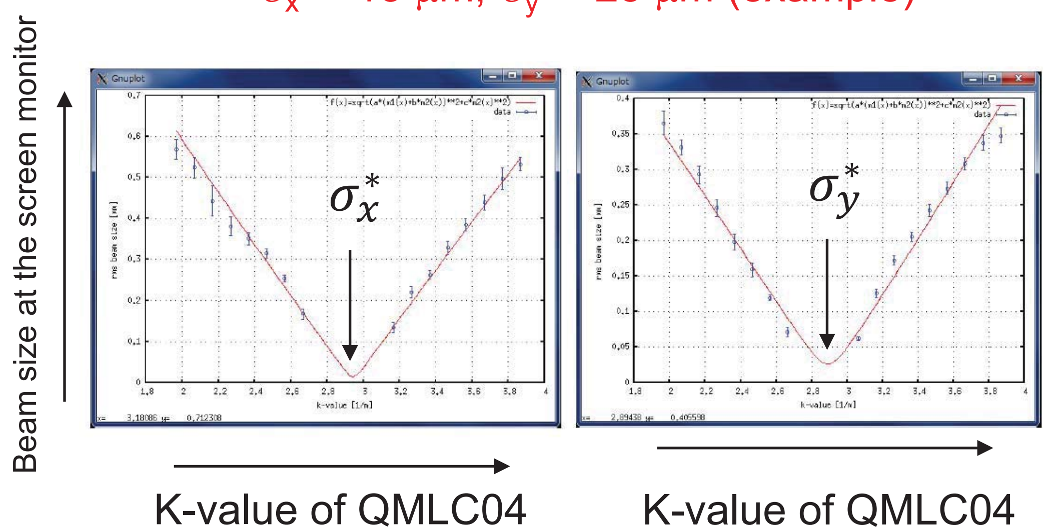
Design optics (example: “70% middle” optics)

$\sigma_x^* = 21\ \mu m$, $\sigma_y^* = 33\ \mu m$ at IP




Beam sizes at IP were estimated from Q-scan data

$\sigma_x^* \sim 13\ \mu m$, $\sigma_y^* \sim 25\ \mu m$ (example)




$\sigma_x^*$, $\sigma_y^*$ < (resolution of the screen monitor)

Bunch charge: 0.5 pC/bunch,
Normalized emittances: $(\varepsilon_{nx}, \varepsilon_{ny})$=(0.47, 0.39) mm·mrad

S. Sakanaka et al., Proc. IPAC-2015, TUBC1

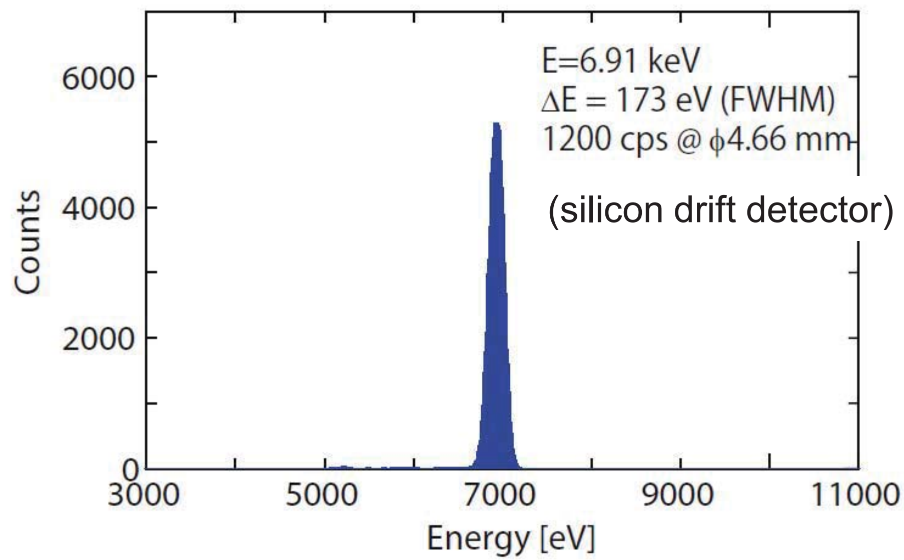
# X-ray Produced by LCS

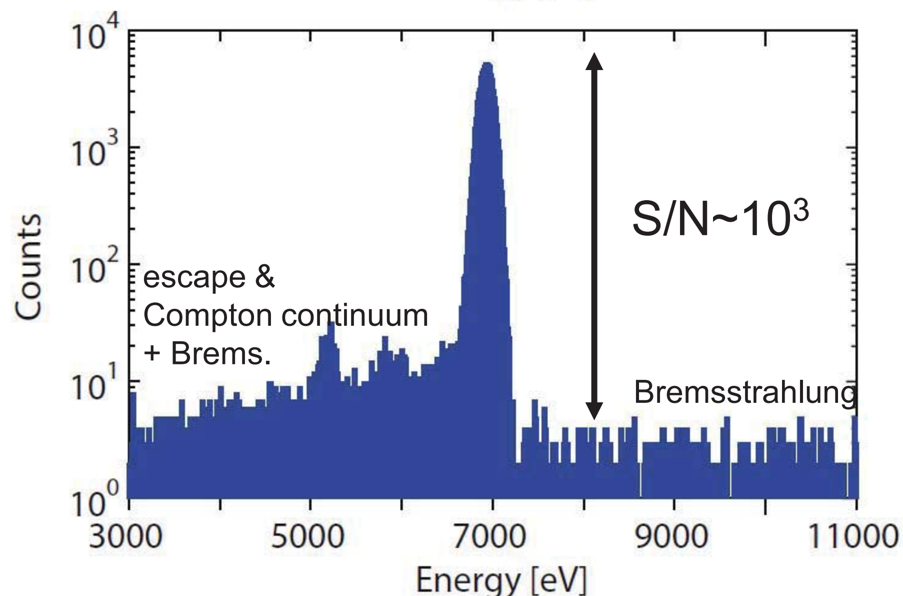
## Parameters of electron beams:

| | |
|---|---|
| Energy [MeV] | 20 |
| Bunch charge [pC] | 0.36 |
| Bunch length [ps, rms] | 2 |
| Spot size [$\mu$m, rms] | 30 |
| Emittance [mm mrad, rms] | 0.4 |
| Repetition Rate [MHz] | 162.5 |
| Beam current [μA] | 58 |

## Parameters of laser (enhanced by cavity):

| | |
|---|---|
| Center wavelength [nm] | 1064 |
| Pulse energy [$\mu$J] | 64 |
| Pulse length [ps, rms] | 5.65 |
| Spot size [$\mu$m, rms] | 30 |
| Collision angle [deg] | 18 |
| Repetition rate [MHz] | 162.5 |
| Intracavity power [kW] | 10 |



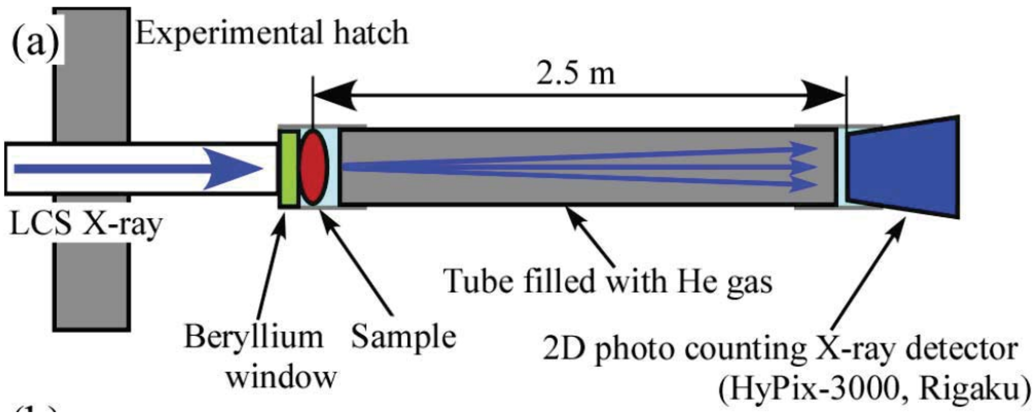

## Results:

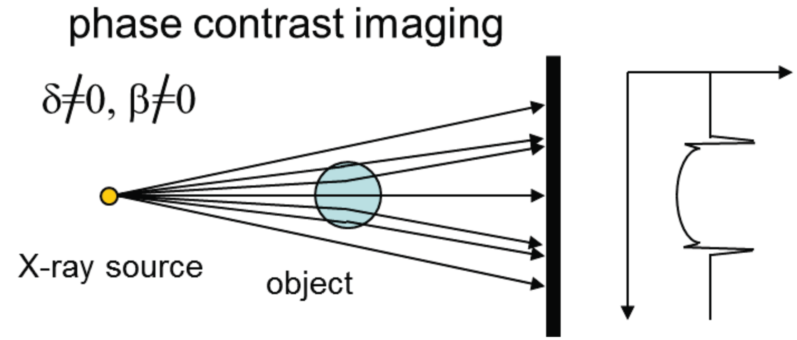
Photon energy = 6.9 keV
Detector count rate = 1200 cps @ϕ4.66mm (*)
Source flux = 4.3 x $10^7$ ph/s (**)

(*) Detector collecting angle is 4.66mm/16.6m = 0.281 mrad
(**) CAIN/EGS simulations with the detector count rate

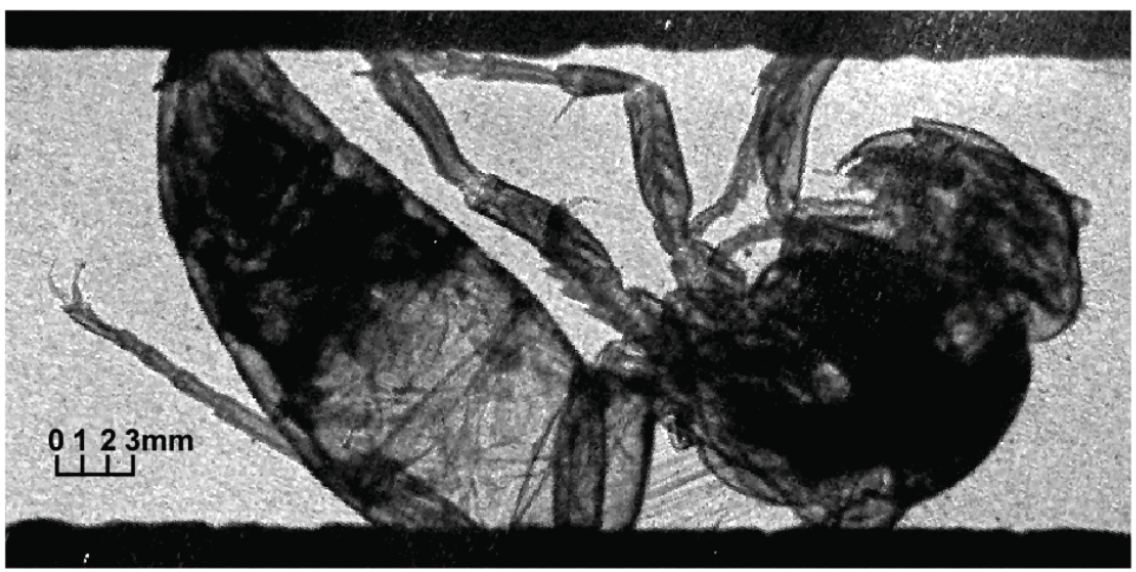
R. Nagai et al., Proc. IPAC-2015, TUPJE002

# X-ray imaging with a LCS beam



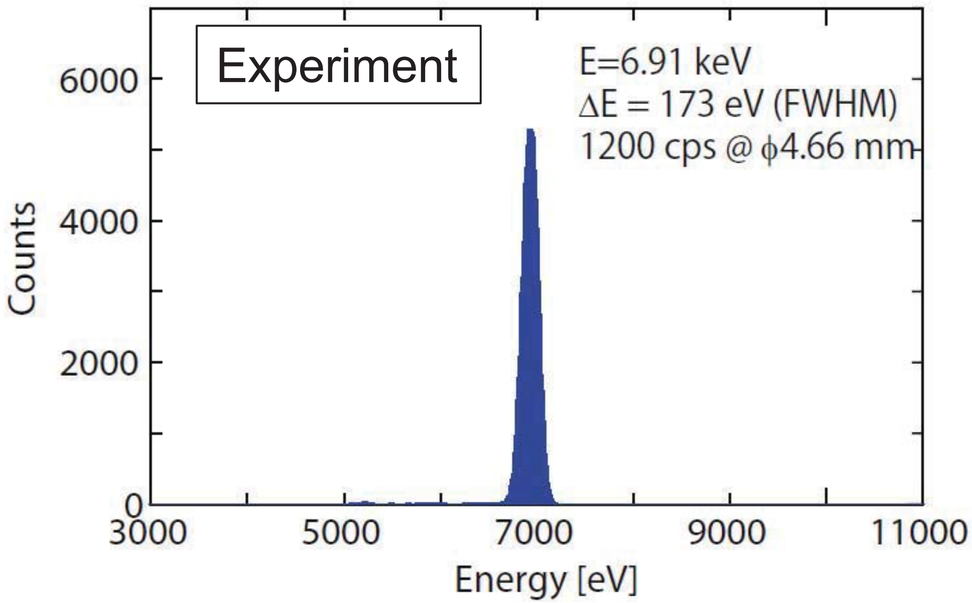

absorption + refraction
→ edge enhancement

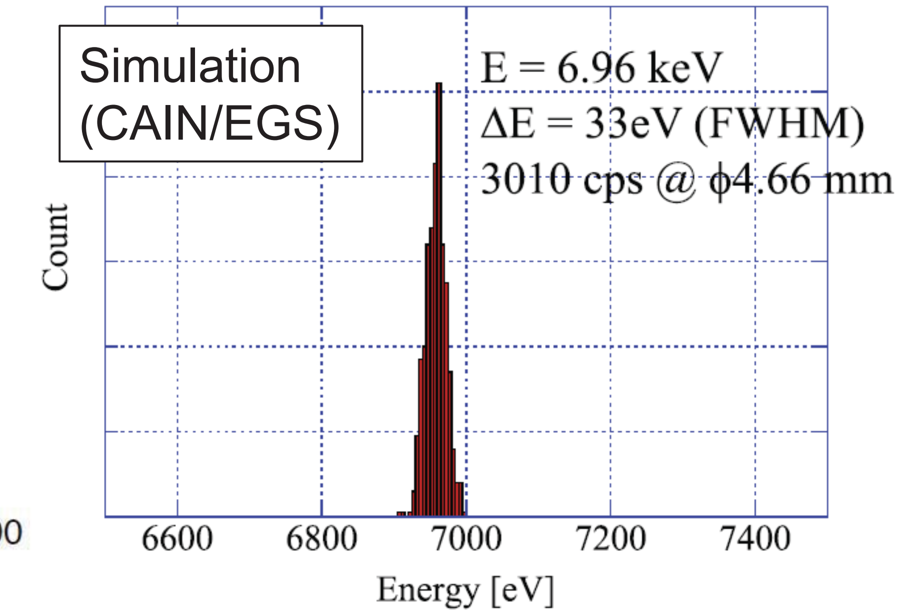



An X-ray image of a hornet taken with LCS-produced X-ray.
Detector: HyPix-3000 from RIGAKU. Detector was apart from the sample by approx. 2.5 m.

A. Kosuge et al., Proc. IPAC-2015, TUPWA066

# Comparison with a simulation




Flux

consistent within a factor of 2.5

Bandwidth

detector resolution = 153eV@5.9keV (Fe-55)

Assuming quadratic nature for convolution of width, the energy width of the LCS photon beam is estimated to be

$$\sqrt{173^2 - 153^2} = 81\ \mathrm{eV}$$

We consider the detector resolution is not enough.
We plant to make another experiment with a crystal monochromator.

# Summary

- ERL is an ideal driver for laser Compton sources.
  - small emittance & high-average current
- Application of LCS $\gamma$-ray to nondestructive detection and measurement of nuclear material is under proposal.
  - high flux and narrow bandwidth
- Phase contrast imaging with LCS X-ray is also an attractive application.
  - round beam from a small-size source
- Generation of LCS X-ray has been demonstrated at cERL.
  - Source flux $4 \times 10^7$ ph/s with 58 $\mu$A electron & 10 kW laser beams
  - Can be scaled to $10^{10}$ ph/s for 10 mA electron beam
- Efforts continue at cERL towards the higher flux of LCS.